PERFORMANCE AND EMISSION OF COATED POROUS MEDIUM BURNER WITH COGENERATION

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PERFORMANCE AND EMISSION OF COATED POROUS MEDIUM BURNER WITH COGENERATION

by

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LIST OF ABBREVIATIONS

ANSI	American National Standard Institute
BIS	Bureau of Indian Standard
CAD	Computer Aided Design
CCHP	combined cooling heat and power
CFD	Computational fluid dynamics
CHP	combined heat power
CME	Canola methyl ester
CO	Carbon monoxide
CO_2	Carbon dioxide
COu	Undiluted carbon monoxide
CT	computed tomography
DC	dip coating
FAME	Fatty Acid Methyl Ester
LPG	Liquid petroleum gas
lpm	Liter per minute
NO	Nitrogen oxide

PDF	Probability Density Function
PE	Porous emitter
PMC	Porous medium combustion
PMW	pulse width modulator
ppcm	Pores per centimeter
ppm	Parts per million
PRRB	Porous radiant recirculated burner
RFPB	Reciprocal Flow Porous Burner
RME	rapeseed-oil methyl ester
SCC	consolidation casting
SEM	scanning electron microscopy
SME	Soy methyl ester
TE	Thermoelectric
TPV	Thermo photo voltaic
UDF	user-defined functions
UHC	Unburned hydrocarbons
XRD	X-ray diffraction

LIST OF SYMBOLS

c_p , c_v	Heat capacity at constant pressure, volume (J/kg-K)
d	Diameter, d_p, $d_{m,}$ D_p, particle diameter (m)
Φ	Equivalence ratio
D_H	Hydraulic diameter (m)
H	Total enthalpy (energy/mass, energy/mole)
h	Heat transfer coefficient (W/m^2-K)
h	Species enthalpy, h^o, standard state enthalpy of formation
k	Thermal conductivity (W/m-K)
m	Mass (g, kg)
M_w	Molecular weight (kg/kgmol)
p	Pressure (Pa, atm)
Pe	Peclet number
q	Heat flux (W/m^2))
r	Radius (m)
Re	Reynolds number
T	Temperature (K,˚C)
t	Time (s)
V	Volume (m^3)
μ	Dynamic viscosity (cP, Pa-s)
ν	Kinematic viscosity (m^2 /s)
S_L	laminar flame speed (m/s)

PA	Primary aeration
SA	Secondary aeration
Qin	useful energy (in KW)
η	efficiency
$\overline{x}$	mean
σ_x	standard deviation
$\sigma_{\bar{x}}$	Standard error
R_L	Variable resistor

PRESTASI DAN PELEPASAN ASAP OLEH PEMBAKAR MEDIUM BERLIANG BERSADUR DENGAN PENJANAAN BERSAMA

ABSTRAK

Pemanasan global telah membawa kepada perubahan iklim dunia. Peningkatan jumlah karbon dioksida dan gas rumah hijau yang dikeluarkan oleh pembakaran bahan api fosil telah dikenal pasti sebagai antara penyumbang utama kepada isu ini. Walaupun kos dan sumber bahan api hidrokarbon (HC) turun dan naik, ia telah digunakan secara meluas. Tambahan pula, bahan api HC untuk aplikasi domestik seperti dalam pembakar gas konvensional mempunyai kesan jangka panjang ke atas kesihatan pengguna. Siasatan ujikaji telah dijalankan untuk meneroka alternatif penggunaan bahan api HC dengan kaedah pembakaran yang lebih baik. Dalam tesis ini, penggunaan pembakar medium berliang untuk aplikasi domestik telah dikaji. Penambahbaikan dilakukan pada pembakar yang digunakan dalam kajian ini dengan memperkenalkan sistem penjanaan bersama. Sistem ini menggunakan sel-sel termoelektrik (TE) untuk menjana tenaga elektrik daripada pembakar medium berliang mudah alih. Kepingan seramik alumina berliang digunakan semasa eksperimen. Pembakaran dikawal semasa eksperimen dengan menggunakan nisbah kesetaraan antara 0.8-1.3. Sel-sel TE menyerap haba di dinding pembakar. Sel ini disambung kepada sistem pengecas TE untuk menyalurkan kuasa kepada telefon bimbit yang menggunakan bateri lithium-ion. Suhu api meningkat dengan jumlah bahan api yang dibekalkan mengikut nisbah kesetaraan yang telah ditetapkan. Keputusan mengesahkan pembakar medium berliang boleh digunakan untuk pemanasan dan pengecasan telefon bimbit. Trend menurun juga dilihat ke atas pelepasan gas CO dan CO terlarut apabila jumlah bahan api meningkat. Keputusan

eksperimen menunjukkan persamaan dengan trend dalam kajian sebelumnya. Pelepasan NOx berada dalam julat yang boleh diterima. Didapati bahawa nilai suhu permukaan substrat alumina adalah sebanyak 675.7°C diukur daripada eksperimen dan 710°C daripada simulasi berkomputer (CFD) dengan perbezaan sebanyak 4.8%. Manakala jumlah NOx direkodkan oleh eksperimen adalah pada 5 ppm dan keputusan yang dihasilkan daripada CFD adalah pada 7.05 ppm dengan perbezaan sebanyak 30%. Nilai CO daripada CFD pula berada dalam julat yang boleh diterima.

Siasatan lanjut mengenai kesan saduran berasaskan SiC, Nickel dan Chromium ke atas pembakar medium berliang telah dilakukan. Satu teknik rendaman telah digunakan untuk menyadurkan SiC-, Ni, dan Cr- semasa pra-sinter substrat Al_2O_3 berliang. Keputusan menunjukkan peningkatan ketara terhadap suhu api permukaan dan pelepasan asap yang minimum berbanding tanpa saduran. Nilai kapasiti haba SiC menyumbang kepada penyimpanan haba yang lebih baik apabila disadur dengan ke atas Al_2O_3. Suhu api permukaan tertinggi dicatatkan pada satu kadar aliran bahan api yang tetap adalah 750ºC untuk saduran SiC, 741ºC untuk saduran Chromium dan 739°C untuk saduran Ni manakala tanpa saduran hanya mencatatkan suhu sebanyak 634ºC. Peningkatan 18% pada suhu api permukaan dicatatkan bagi substrat bersadur SiC berbanding tanpa saduran dan mengurangkan pelepasan CO, CO terlarut dan NOx. Disamping itu, substrat bersadur SiC menghasilkan output kuasa keseluruhan terbaik berbanding tidak bersadur. Analisa berangka juga menunjukkan keputusan yang sama di mana suhu api permukaan kesan daripada saduran yang diramalkan oleh simulasi CFD menunjukkan 3.5% kepada 6.1% perbezaan berbanding keputusan eksperimen dengan saduran SiC mengekalkan suhu yang paling tinggi. Pelepasan gas CO dan NOx juga dapat diramalkan dalam julat yang boleh diterima.

PERFORMANCE AND EMISSION OF COATED POROUS MEDIUM BURNER WITH COGENERATION

ABSTRACT

Global warming has led to the change of world climate. The increased volumes of carbon dioxide and other greenhouse gases released by the burning of fossil fuels have been identified as among the primary contributor to this issue. Although the cost and source of the hydrocarbon (HC) fuels are fluctuating, it has been widely used. Furthermore, the used of HC fuels for domestic application such as in conventional gas burner relates to long term effect on health of the user. An experimental investigation was conducted to explore the alternative way of using HC fuel with improved method of combustion. In this thesis, the application of porous medium burner for domestic application has been studied. Further enhancement has been done on the burner by enabling cogeneration system. This system utilized Thermoelectric (TE) cells to generate electricity from portable porous medium burner. Alumina ceramic PM foam is used during the experiment. Combustion was controlled during the experiment by using the equivalence ratio of in between 0.8 to 1.3. The TE cells were attached to burner wall to absorb heat. The TE cells were connected to TE charger system to manage power output and to charge a mobile phone with a lithium-ion battery. The flame temperature increased with the amount of supplied fuel for the given equivalence ratios. Results show that the PM burner can be used for heating and cell phone charging. The decreasing trend was observed in CO and undiluted CO emission as fuel increased. The experimental result shows similarities with the trends in previous works. NOx emissions were in the acceptable range. It is found that surface temperature value of plain alumina substrate was 675.7

ºC from experiment and 710 ºC from CFD simulation with 4.8% different. While the amount of NOx recorded by experiment was at 5 ppm and the results produced from CFD was at 7.05 ppm with 30% different. The CO value from CFD was in the acceptable range.

Further investigation on the effect of Silicon Carbide (SiC-), Nickel (Ni-), and Chromium (Cr-) based coating to performance of porous medium burner are evaluated. A dip-coating technique was used to coat SiC-, Ni-, and Cr- powders on a pre-sintered porous Al_2O_3 substrate. The results show a significant improvement in surface flame temperature and combustion emissions over the plain Al_2O_3 substrate. The heat capacity of SiC coating materials contributed to better heat released when used with plain Al_2O_3 substrate. The highest recorded surface flame temperature at fixed flow rate was 750 ºC for SiC-coated, 741 ºC for Cr-coated, 739 ºC for Ni-coated and plain substrate registered a temperature of only 634 ºC. An 18% increase in flame temperature was recorded for SiC-coated substrate when compared to the plain substrate. Moreover, coated substrate reduced emissions of CO, undiluted CO and NOx. It was also found that, SiC-coated substrate reported best overall power output generated when compared to the plain substrate. The flame temperatures produced due to coating is predicted by CFD simulation shows 3.5 % to 6.1 % different as compared to experimental results with SiC coated. It also maintained the highest flame temperature obtained from CFD. The CO and NOx emission have also been predicted from the CFD with acceptable range.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Nowadays the authorities impose strict conditions on air pollution caused by hazardous gases released from industrial and domestic combustion devices, due to its effect on global warming. It is rather impossible to avoid carbon footprint from combustion products such as carbon dioxide (CO_2) as long as hydrocarbon (HC) fuels are consume in daily usage. However, the concentration of other harmful combustion products such as CO and NO_x is a major concern, since most of users of this fuel are the domestic consumers who would be affected on account of its inhalation. A better combustion and thermal efficiency produced by a burner is the indicator of better emission released. For these reasons, new technique in combustion involving domestic burner has been studied. One of the techniques which have demonstrated an improvement in combustion is porous medium combustion technique. It has been reported in one of the latest work involving porous medium combustion that low NOx and CO products can be achieved in a flexible range of equivalence ratio and thermal loads (Keramiotis et al. 2011a). Thus, introduction of porous medium burner based combustion technology has provided with a viable alternative towards low emission domestic combustion. The first work on the application of porous medium burner was reported by Bone (1912), Lucke (1913) and Hays (1933) for constructing cooking stoves on stationary combustion in an inert porous medium (Mohamad 2005) whereas the concept of using ceramic in porous medium burner was introduced by Weinberg (1971). Andersen et al.(1990) confirmed the advantages of porous medium burner over conventional free flame burners.

1.2 Combustion in Porous Media, Advantages, Technology and Application

Global warming has resulted in increased restrictions on air pollution caused by hazardous gases released from industrial and domestic combustion devices. The concentration of harmful combustion products such as CO and NO_x predominantly effect women of the household, who make use of hydrocarbon fuels, such as LPG and butane for daily domestic use. The ceramic foam having porous structure has many advantages in combustion. It increases surface area per unit volume, which in turn helps premixing of reactants, preheating and thus optimizes exothermic reaction with the formation of complete reaction products. The unique feature of porous medium combustion is that it is clean and has very high combustion efficiency (Francisco et al. 2009, Catapan et al. 2011, Francisco et al. 2013, Yu et al. 2013). For domestic application of porous medium burners, the use of ceramic spheres and foam are widely used (Muhad et al. 2011, Pantangi et al. 2011, Mueller et al. 2013, Yu et al. 2013). These types of ceramics are often made from alumina, porcelain and silicon carbide with various size and shape. Porous medium is arranged in different layers based on Peclet number to avoid flashback and to promote heat recirculation throughout the combustion process.

Another main concern of researchers is that the heat generated is not fully utilized and majority of the heat is dissipated to environment. Therefore, many recent studies focused on cogeneration system which utilizes the heat provided by burner and convert it into other forms of energy. Thermoelectric (TE) generators operate by utilizing the Seebeck effect which produces electric voltage when subjected to temperature gradient across two dissimilar metals joined together. Consequently, the voltage and power output can be further increased provided the temperature difference across the device is also increased. Thermo photovoltaic (TPV) cells uses heat dissipated to the surrounding walls of the burner and converts it into useful voltage. An output power density of about 1.03 W/cm^2 was produced by the TPV using the radiation energy released from the micro-combustor.

1.3 Problem Statement

The usage of hydrocarbon fuels such as LPG and butane by the conventional burner can be reduced by using porous medium burner where it is found that with the same amount of fuel, the heat energy produced can be increased thus reducing the emission, cost and time consuming for cooking or heating. This has been recently proven by Mujeebu et al.(2011a) by using his experimental setup where only 46% of thermal efficiency produced by conventional burner as compared to porous burner which has achieved around 56% to 63% of thermal efficiency at the same amount of fuel inlet. However, these values of thermal efficiency from combustion in porous media can be further increased if proper design of the porous burner is considered. Similar findings involving experimental investigation on the performance of a porous radiant burner (PRB) used in an LPG cooking stove has also been presented by Muthukumar et al. (2011). The use of PRB showed a higher thermal efficiency than that of the conventional burner. Considering its benefits, Patangi et al. (2011) also employed PRB by using LPG as fuel. Many other studies also reported that the use of porous structures such as ceramic porous foam helps achieve higher energy release and lower emissions of CO and NO_x (Mossbauer et al. 2002, Trimis 2006, Wood and Harris 2008). Yet, the thermal efficiency achieved in their study can still be debated. From general observation, the usage of butane fuel in cartridge for portable conventional burner has been widely used. The application of porous medium combustion technique in portable conventional burner may also increase the thermal efficiency. This can be done by applying coating material to the porous media. Only single work done by Mueller et al (2013) focused on the use of SiC coating porous burner but the work focused only for power generation.

Another way of increasing the efficiency of the porous medium burner is by minimizing the heat losses. Even though the porous burner can be fully insulated, the design of the conventional domestic burner available without insulation and thus provide restriction in cost of manufacture. Therefore, combining both heat and electrical power generation by porous medium burner can be introduced to increase the efficiency and include extra features to the burner. As examples, Qiu and Hayden (2003) have carried out experimental study to generate electrical power for household applications while Chou et al. (2010) and Li et al. (2010a) evaluated a micro porous medium combustor with TPV to absorb useful radiation energy from the micro-combustor.

Therefore, an effort has been taken in this study to improve the performance of previous porous medium burner reported. Three different types of coating materials including SiC, Nickel and Chromium have been used with plain alumina substrate. The hexagonal design of the coated porous medium burner incorporated the micro cogeneration system to the burner wall. This allow the thermoelectric (TE) cells to convert heat into useful electricity which in turn can be used for small low power electrical devices such as mobile phone charger, LED lamp and many more. Effects of each before and after combustion has been further investigated in term of performance, emission, power generation and microstructure of porous medium. The results produced are very promising as compared to uncoated porous medium. A CFD model of this coated porous burner has been developed as well for numerical analysis by incorporating simple method to find the effect of coating on flame temperature as well as CO and NOx emission which may help in designing coated porous medium burner in coming future.

1.4 Objectives of the study

The objectives of the study are listed below,

I. To devise a porous medium burner to be used for indoor or outdoor activities using butane gas in cartridge as fuel.

II. To obtain the maximum flame temperature and the minimum CO and NOx emission produced by porous medium burner by using naturally aspirated and compressed air supply.

III. To measure power output from cogeneration system attached to porous medium burner using thermoelectric (TE) cells.

IV. To investigate the flame temperature, CO and NOx emission as well as the power output from cogeneration produced by using different types of coated porous media.

V. To conduct numerical analysis using fluent code on flame temperature, CO and NOx emission from porous medium burner on different types of coated porous media.

1.5 Scope of work

The scope and limitation of the study are given below,

I. The fabricated burner is only designed for domestic application.

II. Porous media used in this study is limited to foam type ceramic materials.

III. Only butane gas was used throughout the tests with lean and rich equivalence ratios varying 0.8 to 1.3.

IV. The micro cogeneration system used thermoelectric (TE) cells to generate electrical power after thorough study between TE and TPV.

V. Coating materials that have been used consist of silicon carbide (SiC), chromium (Cr) and Nickel (Ni) ,have minor effect on oxidation when used for combustion medium.

VI. Numerical analysis using fluent code with standard governing equation and global reaction mechanism was conducted in this study.

1.6 Thesis overview

This thesis consists of five chapters with first chapter describing general aspects about the complete work done. The literature review in chapter two summarizes the research trends and findings with regard to the study of porous medium combustion, especially involving domestic burners. The porous media and porous medium combustion were defined and described briefly for better understanding. The previous experimental and numerical work was discussed separately to enable the understanding of the porous medium combustion development. In chapter three, a detail explanation on the work done was justified. The major and salient components have been presented according to the experimental order with general procedures given for repeatability. Some basic equations are given both for experimental and numerical analysis where ever necessary.

Entire results and discussion are presented in chapter four. In the beginning of this chapter discussion on the steady state time required for flame stabilization of porous medium burner, cogeneration system involving thermoelectric and thermo photovoltaic cells are dealt. It has been expanded to the discuss results produced by two different air supply system for the porous medium burner, which are naturally aspirated and compressed air system. The results from different air supply system are discussed on flame temperature and emission produced, as well as cogeneration capabilities. These results can be used for the selection of air supply system, cogeneration device and cooling method.

Another part of chapter number four deals with improvement made on the porous medium burner by using different coatings. The effect of coatings materials to the alumina porous medium burner were discussed again in term of maximum surface flame temperature produced, emissions, open circuit voltages and load power output produced by cogeneration. The numerical prediction on the coating effects to porous medium burner performance was well included. The porous medium burner prototype development has also presented in the end of chapter four. Finally in chapter five conclusions has been made with respect to the objectives listed earlier to this chapter.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, a thorough review of porous media and its application in combustion is presented. The application of new technology such as thermoelectric and thermo photovoltaic cogeneration in tandem with porous medium combustion is also revised according to recent work, which have already been published. Also, the chapter discusses the progress of numerical method to study the combustion in porous medium. Besides, the recent advances regarding the improvement made in porous media burner is also considered at the end of this chapter with some highlights on the previous works carried out at Porous Media Combustion Laboratory of Universiti Sains Malaysia.

2.2 Global warming, environment and well being

Global warming due to the greenhouse effect was the problem caused by the emission of hydrocarbon (HC) fuels combustion. HC combustion releases a large amount of carbon dioxide CO_2 to the air, therefore HC fuel must be reduced by increasing efficiency of combustion. By doing this way, the amount of HC fuels emission can be controlled without compromising on quality of energy from the HC fuel. Increase in population has also contribute to the increase of HC fuels demand especially LPG for domestic or household burner. This has been identified among the major source of pollution including in industrial burner. Beside the greenhouse effect, the emission from fossil fuels normally HC fuel provide hazardous to the consumer health. This is due to the incomplete combustion normally from domestic burner that produced carbon monoxide (CO) and nitric oxide (NOx), in other aspect, the depletion of natural resources of HC fuels become another concern. Even though fuel is priced, the fossil fuel resources are still facing the depletion, which will continue for long time if proper precautions are not considered. Therefore, it can be concluded that without proper usage of combustion burner, the combustion will increased pollution which has its effect on health and environment. Existing means of domestic cooking must be improved through research on reducing harmful effects and pollution. By utilizing energy efficiency devices such as porous medium burner, it can be an optional for the user to provide better life by reducing pollutions, which may cause hazardous to the health and environment. Better combustion process in porous burner is always seen in comparison with conventional burner, which indirectly reduces the expenses on fuels.

2.3 Porous media as a medium of combustion

Packed beds, wire mesh, wools, sponge or foam are commonly used as a porous medium. Porous medium can be defined as a material with voids in different structure. The voids in porous medium is measured in terms of porosity, allows air or liquid to pass through it and this capability is known as permeability. There are many well-known applications involving porous material such as water filter, heat exchanger, cleaning agent to absorb oil spilled, inorganic membrane and many more. Filtration combustion is another important application of porous media. It is commonly known as porous medium combustion.

Porous medium can be made from metal, ceramics, plastic or any materials. However, only high temperature resistance materials such as metal and ceramic are suitable to be used as medium of combustion. The selection between porous metal and ceramics materials is based on the application of the burner. Metallic materials have less thermal stability and high thermal inertia. Thus, metal porous materials were less used for porous medium combustion. The porous ceramic are frequently used than metals in porous burners based on the temperature stability produced during combustion with comparatively acceptable emission (Tierney and Harris 2009). The work on combustion using ceramic porous media has been reviewed by Wood and Harris (2008). Recently, several studies have established the applications of porous ceramic inert media in combustion (Keramiotis and Founti 2013b, Yu et al. 2013, Gao et al. 2014a).

2.3.1 Preparation of porous ceramic foam

Among types of porous media, foam types are very well used these days. The unique structure of the cellular porous ceramic provide better properties such as low density, high porosity, low thermal conductivity, high permeability, high specific surface area and high temperature resistance (Jamaludin et al.2015a). Porous ceramic foam consists of interconnected skeleton as shown in SEM images in Fig. 2.1.

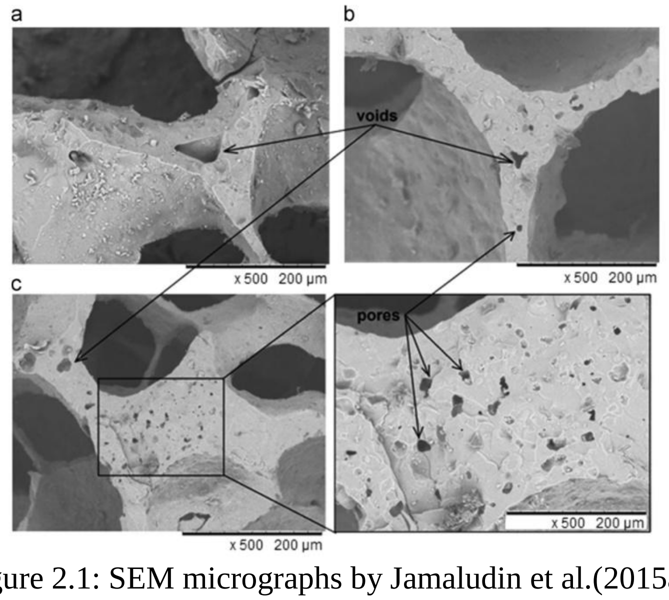


Figure 2.1: SEM micrographs by Jamaludin et al.(2015a).

Porous ceramics are made from materials such as kaolin (Nandi et al. 2008), porcelain (Muhamad et al. 2008, García-Ten et al. 2012), alumina (Khattab et al. 2012), mullite (Yang et al. 2012), silicon carbide (SiC) (Dey et al. 2011), and zirconia-based ceramics (Garrido et al. 2009). Pickenacker et al. (1999) has identified alumina, silicon carbide (SiC), and zirconium dioxide (ZrO_2) to be used as medium of combustion. Among them, SiC have shown good thermal shock resistance, mechanical strength, and conductive heat transport. Howell et al. (1996) proposed silicon nitride, mullite and cordierite, as suitable materials for porous medium combustion. Latest work on the improvement of SiC foam preparation for burner application has been done by Fuessel et al. (2011). Randrianalisoa et al.(2009) provides a comprehensive study through one-dimensional porous burner configuration. Open cells foam materials are used for selection to optimize a porous radiant burner (PRB) design with regard to the environmentally driven requirement. The work involves the optimization of the PRB efficiency criteria and rate of pollutant allowable limit. However, the possibilities of using multi layers with increase or decrease of porosity have to be investigated from their work.

There are many different methods in producing porous ceramics foam such as the replication technique (Muhamad Nor et al. 2008, Quintero et al. 2009, Kim et al. 2010), freeze casting (Jing et al. 2010), extrusion (Moon et al. 2011), compaction (Taktak et al. 2011), and starch consolidation casting (SCC) (Khattab et al. 2012). Among them, the polymeric foam replication technique using highly porous polymer foam (typically polyurethane (PU)) is very commonly employed.

2.3.2 The combustion reaction mechanism in porous medium

The thermo-physical properties of porous medium provide greater combustion efficiency compared to free flame combustion. Combustion process involves physical and chemical reaction mechanism of fuel and oxidizer. In porous media, the combustion process can be described through the way air and fuel is mixed and preheated physically in the porous medium. This promotes combustion reaction, which is due to preheated air fuel mixture providing appropriate condition for the exothermic reaction to take place. The unique features of combustion in porous media have been summarized by Mohamad (2005), as given below.

- The ability to customize the thermo-physical properties of porous medium such as thermal conductivity and thermal capacity by using different material and structures according to burner application.
- Provide heat transfer by radiation emitted from solid porous material which increased overall heat transfer. More heat absorbed by radiation reduced NOx pollutant as flame temperature reduced.
- Solid porous structures create turbulent flow and generate small vortices inside the voids. This promotes enhancement of momentum heat and mass transfer. Furthermore, surface area per unit volume of porous medium which is relatively large will facilitate energy and momentum transfer between solid and fluid phases.
- By adjusting permeability of porous medium, pressure difference through the porous material can be controlled. This becomes a critical issue when dealing with a low pressure inlet of air fuel mixture into porous medium burner.
- Adsorption may occur at the surface of porous medium to give catalytic effect on the combustion reaction.

An important criterion known as excess enthalpy flame is also observed from porous medium combustion. Firstly, the preceded heat produced from the combustion is retained in porous medium solid structures. Then, it will simultaneously preheat the incoming inlet of air fuel mixture. The heat recirculation inside porous media combustion will increase the enthalpy of combustion and therefore produce the excess enthalpy flame. Theoretical and experimental studies initiated by Takeno et al. (1981) and Kotani and Takeno (1982) to validate this phenomena in porous medium combustion. Latest work performed by Shi et al. (2009), Wang et al. (2009) and Horng et al. (2012) were pinned under various systems and conditions. The theory of excess enthalpy can be explained using equation given below (Weinberg 1971),

$$\int_{T_o}^{T_f} C_p \, dT = Q_c + Q_a = H_f - H_o \qquad (2.1)$$

where, T_f is the final temperature, T_0 is the initial temperature, Q_c is heat released by chemical energy conversion, Q_a is the energy added, H_f and H_0 are enthalpy at two states. The heat transfer mechanism and temperature profile in porous medium combustion is illustrated in Fig.2.2. The combustion in porous media can be classified according to the combustion flame. The common terms used are premixed, partially premixed and non-premixed combustion flame. Most numerical and experimental study of porous medium burners including latest work by Li et al. (2011), Mendes et al. (2011), Djordjevic et al. (2012), Xia et al. (2012), Kokubun et al. (2013), Yu et al.(2013) and Gao et al. (2014b) used premixed combustion with intention to control the flame stabilization as well as to reduce exhaust gas emission. The premixed combustion can be described as a mixing of fuel or reactant with oxidizer normally oxygen before the air fuel mixture reaching the reaction zone or specifically the flame front. Partially premixed combustion can be simply understood as combustion producing neither premixed nor non-premixed flame.

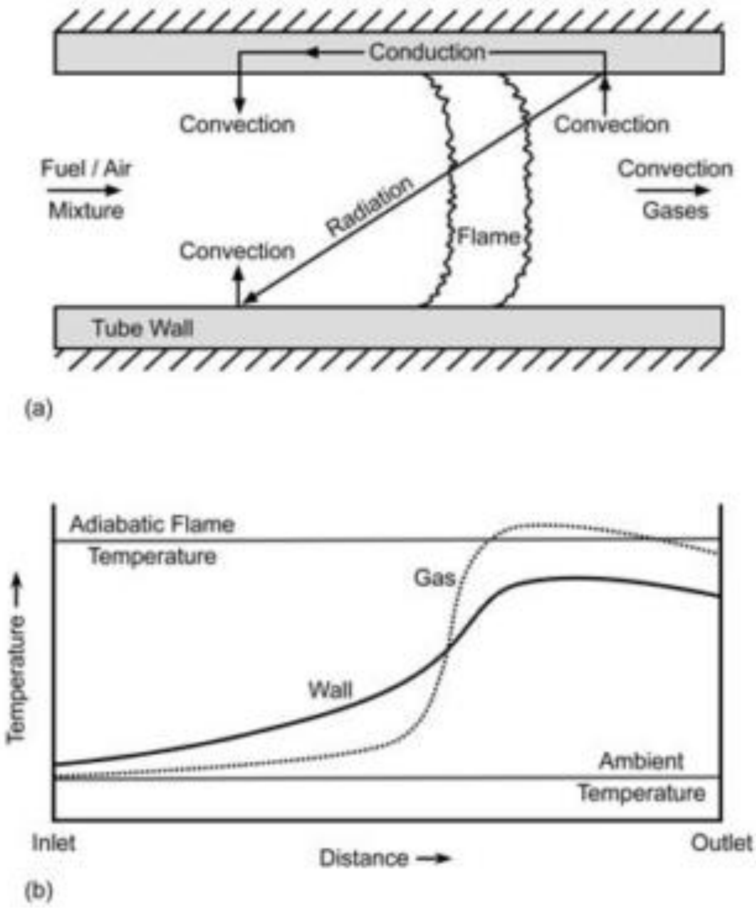


Figure 2.2: Combustion of porous medium in tube (a) Heat transfer mechanism (b) corresponding temperature profile as described by Viskanta (2011) and Viskanta and Gore (2000).

This is because of the fact that fuel is supplied to oxidizer just before entering the reaction zone. The non-premixed combustion refers to the process of utilizing air and fuel being supplied separately into reaction zone to react such as in coal furnace or candle light combustion flame. The Laminar non-premixed flame is also known as laminar diffusion flame. The premixing system of porous medium burner for air and fuel depends on valve controlling the inlet fuel and air or by using self-aspirating system by injecting fuel with nozzle to the air before entering reaction zone, such as in Bunsen burner or domestic gas stove. The characteristic of temperature profiles of no premixed porous medium combustion has been done by Wang et al. (2011).

Combustion in porous media also depends on the orientation of the porous foam and porosity of the foam. The Peclet Number (Pe) is used to create two different zone known as preheat zone, Pe<65 and reaction zone Pe>65 (Trimis and Durst 1996). The combustion reaction will only occur in reaction zone where the combustion flame exists inside or on the surface of the porous medium foam. Therefore, the mode of combustion reaction in porous media has been identified as matrix stabilized (inside the porous medium) or surface stabilized (on the surface of porous medium). The matrix stabilized combustion is also known as submerged flame combustion (Mujeebu et al. 2011b). The Peclet number Pe is calculated from equation below.

$$Pe = \left(S_L d_m C_p \rho\right)/k \qquad (2.2)$$

Where S_L=laminar flame speed, d_m=equivalent diameter of the average hollow space of the porous material, C_p= specific heat of the gas mixture ρ= density of the gas mixture and k=is the thermal conductivity coefficient of the gas mixture.

2.4 Types of fuels used in porous medium combustion

Most burners including porous medium burner uses gas and liquid fuels which are generally extracted from fossil fuels. Depletion of energy sources is a major concern nowadays. The cost of using fossil fuel has increased significantly with the increase in the global demand due to the growth of world population and rapid development in industrial activities. Porous medium combustion has been proven as the best way of using fossil fuel efficiently. With the same amount of fuel, heat generated is higher than conventional burners. The use of porous medium burner with bio fuel is expected to further increase the porous medium burner efficiency.

2.4.1 Gas combustion

In porous medium combustion, gas fuel such as methane, butane, propane and LPG are often used in many applications. LPG gas is popular in domestic gas burner applications, while butane or propane is suitable to be used for portable burners. Combustion by using LPG in porous medium burner have been carried out by Charoensuk and Lapirattanakun (2011), Muthukumar et al. (2011), Pantangi et al. (2011) and Mujeebu et al. (2013). Most LPG combustion in porous medium concentrate on the application for domestic use such as porous medium gas stove (Mujeebu et al. 2011b, Muthukumar et al. 2011 and Pantangi et al. 2011).

A work by Cerri et al. (2000) on porous medium combustion by methane has been conducted on two ceramic foam burners with and without catalytic. It was found that HC concentrations always remained low on both cases. Gao et al. (2011a) has published a few work on methane and propane gas combustion with latest work by using two layer porous burner with different foam (Gao et al. 2014c). There are many others recent works (Li and Hsu 2006, Zhu et al. 2007, Alavandi and Agrawal 2008, Dobrego et al. 2008, Ma et al. 2010, Wang et al. 2011 and Xu et al. 2012) using methane as fuel in porous medium combustion describing methane as the most allowable gas to be produced and used in many ways especially with porous medium burner.

Toledo et al. 2011 used butane fuel and wood pellets to produce syngas through rich and ultra-rich combustion in an inert porous medium. Propane also has been used by Toledo et al. (2009) to produce hydrogen by using combustion in porous medium. Other propane combustion in porous medium has been done by Korzhavin et al. (2005), Kakutkina et al. (2006), Shi et al. (2008), Xu et al. (2009) and Xu et al. (2011a).

2.4.2 Liquid combustion

The combustion of liquid fuel in porous burner is less. The use of kerosene fuel in porous burner is tested to suit with domestic burner application normally in rural area where LPG is not available. The problem of using liquid fuel in porous burner is that the liquid fuel needs to be vaporized before entering the porous medium reaction zone to produce flame such as in gas combustion. A study of kerosene combustion in porous medium has been done experimentally by Vijaykant and Agrawal (2006) using carbon foam with SiC coated. The heat recirculation inside the foam pre vaporizes the liquid kerosene fuel before combustion. It was found that combustion of kerosene in porous medium reduced the emission by improving the vaporization and air fuel premixing. Aviation grade kerosene has been used by Periasamy and Gollahalli (2010) to study the performance and emission in porous medium combustion. The kerosene was injected by using an air-blast atomizer to produce stable flame. From this study, it has been shown that the NOx produced was not dominated by parameter such as equivalence ratio and spray nozzle when porous medium is used. Latest study on kerosene non-spray combustion in porous medium can be found out from work prepared by Wongwatcharaphon et al. (2013)&(2014). Pastore and Mastorakos (2010)&(2011) has provided a study on syngas production through rich combustion of liquid fuel such as n-heptane, diesel oil, kerosene and rapeseed-oil methyl ester (RME) bio-diesel.

Combustion of other liquid fuels such as heptane can be found from work performed by Kaplan and Hall (1995) using a spray nozzle for fuel impingement in porous medium combustion zone. Kamal and Mohamad (2007) have studied on the orientation of the spray nozzle in porous medium with swirled air supply. Porous medium which has been inserted at the burner exit has promoted droplet evaporation while enlarging the recirculation zone before the fuel injector improving mixing and combustion efficiency. Trimis et al. (2001) produced a novel cool flame vaporizer for liquid fuel with porous medium burner. Porous medium combustion in engines performed by Zhao et al. (2009) using CFD to study liquid fuel combustion in compression ignition engine. The study involved two types of porous medium engine and the results have shown that the porous medium temperature and structures have some effect on porous medium compression ignition engines. Krittacom et al. (2011) investigated the evaporation of diesel fuel and its combustion behavior. The fuel drop technique was used. The porous burner (PB) used pebbles with and without porous emitter (PE), where higher temperature profile has been found for PB with PE. More works can be found out from literatures provided by Jugjai and Polmart (2002) and Jugjai and Pongsai (2007) without using spray atomization for liquid porous medium combustion. Heavy oil or crude oil combustion in porous medium has been studied by Cinar et al. (2011).

2.4.3 Bio fuel combustion

Renewable energy source such as bio fuel become significant nowadays. By taking advantages of porous medium combustion, the use of bio fuel can be more efficient. The type of bio fuel that is currently tested in porous burner is vegetable oil (Bakry et al. 2002). There is bio fuel in liquid form such as blended kerosene fuel with palm oil or bio seed fuel. BIOFLAM project (Brehmer et al. 2003 and Heeb et al. 2005) used renewable biodiesel which is also known as a Fatty Acid Methyl Ester (FAME). In this project, a specially designed ceramic premixed liquid fuel porous medium burner was used with cool flame vaporization technique to produce high power modulation with low emission level.

In another work, vegetable (rapeseed) oil as a bio fuel has been tested with porous medium combustion (Bakry et al. 2010a). A prototype integrated vaporizer system with a PIM burner based on the flow velocity flame stabilization technique was built and experimentally investigated. A stable combustion has been observed with the absence of CO emissions recorded. Canola methyl ester (CME) and soy methyl ester (SME) produced from vegetable were among the bio fuel tested in porous medium burner (Barajas et al. 2010). It has been found that the axial flame temperature produced by CME and SME were similar to commercial Jet-A fuel combustion in porous medium burner. However, some clogs were found due to solid particle decomposition stuck in porous medium and on the metal walls of the injector by combustion of CME and SME.

Biogas is another type of renewable energy that can be used with porous medium burner. Due to the low heating value of biogas, the Reciprocal Flow Porous Burner (RFPB) has been used by de Araújo et al. (2013) to increase the efficiency with low emission. A stable combustion was found for both study of methane and biogas combustion, when RFPB is applied, which is also more efficient with low emissions. Some interesting studies related to the use of biogas in porous medium combustion can be found from the work done by Gao et al. (2011b) and Keramiotis and Founti (2013).

2.4.4 Exhaust gas emission from porous medium combustion

The incomplete combustion of fossil fuel which is also known as hydrocarbon (HC) fuel produced unburned hydrocarbon (UHC) and carbon monoxide (CO). Another product of combustion which is dangerous is the nitrogen oxide gas or NOx. This type of gas will only occur at very high temperature where the nitrogen content in the atmospheric air oxidized in combustion flame. Whereas, high temperature combustion crack down the CO into CO_2 in atmospheric air as well as promoting the UHC to be completely burned. Therefore a trade of between CO and NOx in HC fuels existed.

The strategy of using porous medium to cater with the trade-off issue between CO and NOx has been found by Trimis and Durst (1996). By using porous medium, the combustion of HC fuel will be completely burned inside the porous media without leaving any UHC. High temperature combustion flame has been controlled by the use of porous medium and the nitrogen gas oxidation will not exist in the surrounding air avoiding the formation of NOx. A numerical study has been done by Zhou and Pereira (1997) to investigate the NO and CO emission reduction in porous medium. Due to very high temperature inside porous medium solid material, the heat transfer mechanism to the thermal load will be largely due to radiation mode which will not oxidize the nitrogen gas in the air. This phenomenon can be found from studies on porous medium radiant burner where CO and NOx were both in relatively low and in acceptable range (Kaplan and Hall 1995). By manipulating the pressure and temperature of the inlet mixture into porous medium combustion system, the CO can be eliminated and NOx content was remarkably reduced as reported by Bakry et al. (2010b).

2.5 Recent application of porous medium combustion devices

Numerous application of porous medium in combustion devices has been found. Some recent works on major application has been selected to describe the essential of porous medium combustion technology. Water purification is one of the examples of using porous medium combustion technique (Dobrego et al. 2010 and Koznacheev et al. 2011). A new technology of water purification of organic inclusions or solutes by using filtration combustion reactor with alternating flow direction is investigated numerically. An acetone aqueous solution served as a model liquid. Non-catalytic porous burner can be used in syngas production as presented by Pastore and Mastorakos (2011). A two-layer inert porous medium combustor was used and different fuels such as n-heptane, diesel, kerosene and bio-diesel were successfully reformed to syngas in a Zirconia foam burner with conversion efficiency over 60%. Micro heat-recirculating combustor using porous media plate has been designed and tested by Cao et al. (2011a). The micro heat-recirculation combustor has a very important application value in developing the micro gas turbine power generation system. The micro porous media combustor possesses some merits such as wider combustion operation ranges, higher combustion efficiency and lower heat loss ratio and should be an ideal micro combustor for developing the micro gas turbine power generation system (Cao et al. 2011b).

In industrial application heating of large surfaces is mainly required; the use of large surface porous radiant burners is the best candidate (Catapan et al. 2011). However, problem is seen in distributing uniform temperature on large surface. In order to allow for larger surface area burners, a non-uniform velocity profile mechanism for flame stabilization in a porous radiant burner using a single large injection hole is proposed and analysed for a double-layered burner operating in open and closed hot (laboratory-scale furnace, with temperature-controlled, isothermal walls) environments. In both environments, local mean temperatures within the porous medium have been measured. For lower reactant flow rate and ambient temperature the flame shape is conical and anchored at the rim of injection hole. As the volumetric flow rate or furnace temperature is raised, the flame undergoes a transition to a plane flame stabilized near the external burner surface. However, the stability range envelope remains same in both regimes.

Stability of lean combustion in mini-scale porous media combustor with heat recuperation was studied by Xu et al. (2011b). In miniaturization of burners, it is very difficult to organize stable self-sustained combustion. A mini-scale porous media combustor with heat recuperation was set up to study the stability of lean combustion and its emission. The diameter of the porous media was only 20mm and the burner was about 140mm in length. Experimental results showed that when the mass flow rate of the premixed gas was 0.163g/s, the extinction limit was extended to $\Phi=0.40$ in the methane combustion and $\Phi=0.39$ in the propane combustion. For most cases, the emission of CO was lower than 100ppm in both methane and propane combustion. The maximal concentration of NOx was 63ppm in the methane combustion. The ultra-lean combustion was also predicted by a numerical simulation with a 2D two-temperature model. The heat recuperation efficiency η, as high as 40%, made the ultra-lean combustion extremely stable. Although the maximal flame temperature in the porous media reached above 2000K, the exhausts temperature was lower than 900K.

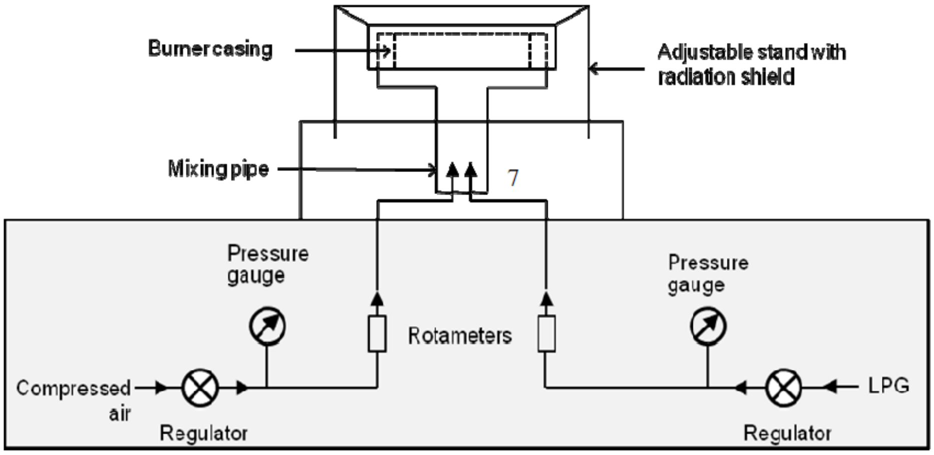
2.5.1 Lean and ultra lean porous medium burners

One of the advantages of having porous medium combustion is its ability to have lean or ultra lean combustion with proper burner system design. By using excess air to fuel ratio with suitable pressure inlet, the exothermic reaction of air fuel mixture in porous media achieves complete combustion with very less emission. The lean combustion reduces the amount of carbon released from the burning of hydrocarbon fuels due to excess of air use age during combustion. Pereira et al. (2010) provides theoretical analysis on ultra lean premixed porous medium burner.

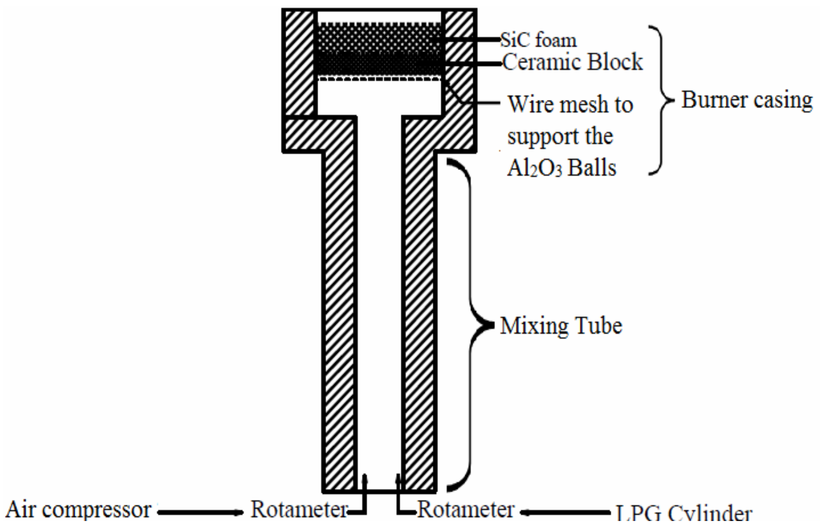
The asymptotic expansion method has been used to investigate the adiabatic premixed flames. Lower flame velocities are found at extremely lean mixtures. The theoretical results have shown that for leaner mixtures, smaller pore sizes and smaller fuel Lewis numbers have reduced super adiabatic effects. Furthermore, there is a minimum super adiabatic temperature for the flame propagation to be possible, which corresponds to lean flammability limit for the premixed combustion in porous inert media. A mini scale porous media combustor has been developed with heat recuperation system. The problem faced by small or mini porous burner to sustain premixed combustion flame has been solved by using heat recuperation technique, where lean combustion at equivalence ratio around 0.4 can be achieved before the flame extinct. This study has been tested on propane and methane. Both fuels produced CO emission less than 100 ppm during the experimental test. Ultra lean combustion model using this burner has been done in 2D temperature model which have shown that there was a possibility of having stable ultra lean combustion in this burner with heat recuperation (Xu et al. 2011b).

2.5.2 Domestic porous medium burner

Some attempts have been found to produce domestic porous medium burner especially on gas stove. A concept of Porous Radiant Re-circulated Burner (PRRB) has been introduced by Jugjai and Sanitjai (1996). The PRRB re-circulated the exhaust gas captured by porous medium to preheat the incoming secondary air supply. Muthukumar et al. (2011) presented a detail study on LPG gas stove using porous medium technology in line with Pantangi et al. (2007) as shown in Fig.2.3.



(a)



(b)

Figure 2.3: (a)&(b) Detail study on LPG gas stove using porous medium technology

However, the design of the stove needs improvement taking into account the application of porous medium burner without compressed air. A practical self aspirating porous burner has been developed and tested by Yoksenakul and Jugjai (2011) using LPG. The porous medium burner has been designed according to the allowable Peclet number calculated from Ergun equation on pressure losses. The burner has demonstrated stabilized flame with surface and submerged combustion flame without flashback. The use of packed bed with sphere balls has reduced the pressure drop for this self aspirating porous medium burner. However, the results of